Development of the X-ray camera for the OGRE sub-orbital rocket

Conference or Workshop Item

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ABSTRACT

Current theories regarding the matter composition of the universe suggest that half of the expected baryonic matter is missing. One region this could be residing in is intergalactic filaments which absorb strongly in the X-ray regime. Present space based technology is limited when it comes to imaging at these wavelengths and so new techniques are required. The Off-Plane Grating Rocket Experiment (OGRE) aims to produce the highest resolution spectrum of the binary star system Capella, a well-known X-ray source, in the soft X-ray range (0.2keV to 2keV). This will be achieved using a specialised payload combining three low technology readiness level components placed on-board a sub-orbital rocket. These three components consist of an array of large format off-plane X-ray diffraction gratings, a Wolter Type 1 mirror made using single crystal silicon, and the use of EM-CCDs to capture soft X-rays. Each of these components have been previously reviewed with OGRE being the first project to utilise them in a space observation mission. This paper focuses on the EM-CCDs (CCD207-40 by e2v) that will be used and their optimisation with a camera purposely designed for OGRE. Electron Multiplying gain curves were produced for the back-illuminated devices at -80°C. Further tests which will need to be carried out are discussed and the impact of the OGRE mission on future projects mentioned.

Keywords: EM-CCD, Off-plane grating, X-ray spectrometry, sub-orbital rocket, OGRE, Capella

1. THE OFF-PLANE GRATING ROCKET EXPERIMENT (OGRE)

The nature of X-ray astronomy requires a highly specialised approach utilising the combination of many technologies in order to collect data relating to a wealth of astronomical research areas. Many abundant metals, such as Iron, Oxygen, Nitrogen and Neon emit and absorb highly in the 0.2keV to 2keV energy range[1] when in their highly ionised states. These photons lie in the soft X-ray region of the electromagnetic spectrum where photons are easily absorbed by the atmosphere, thus requiring a space-based approach.

The Off-Plane Grating Rocket Experiment (OGRE) aims to utilise new technologies to capture soft X-ray spectra from Capella (Figure 1), a well-known source of X-rays, in a space environment. The use of a sub-orbital rocket enables a low cost means for testing potentially high-risk approaches with the hopes that future projects can use a similar approach. The payload will be an off-plane X-ray grating spectrometer which will utilise focusing optics developed by the Goddard Flight Centre, diffraction grating developed by the University of Iowa and Penn State University, and a camera developed by the Open University and XCAM Ltd. which features an array of Electron Multiplying Charged Coupled Devices (EM-CCDs) manufactured by e2v. Together they aim to cover the 0.2keV to 1.9 keV bandpass with a resolution of R$\sim$2000. This would represent a huge step in the spectral performance of soft X-ray detection as well as improving the technology readiness levels (TRL) of the three main components, thus encouraging their use in larger X-ray missions in the future.

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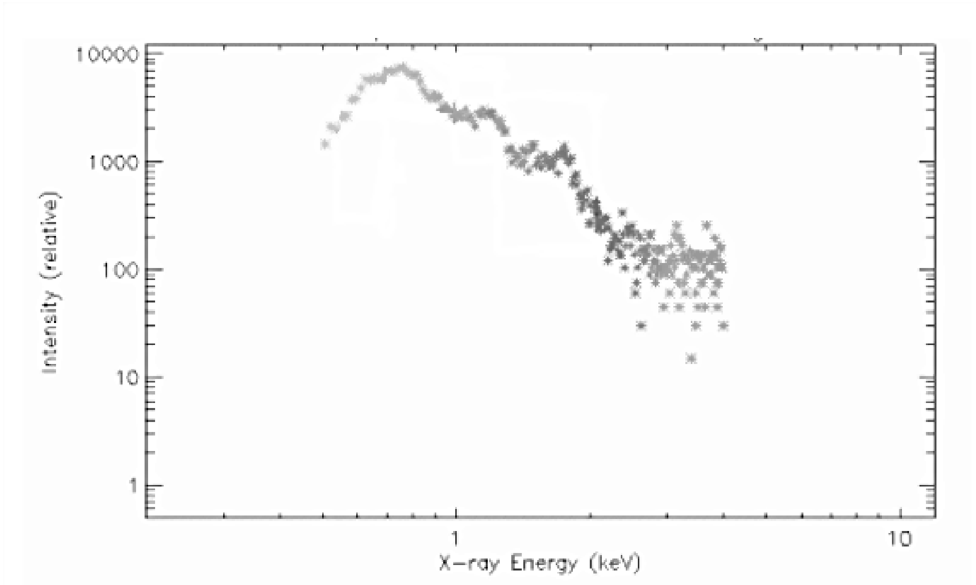

Figure 1. Spectra of Capella in the soft X-ray energy range captured using the ACIS-S detector on board Chandra. The spectrum was obtained using a two-hour exposure.[2]

The Off-Plane Grating Rocket for Extended Source Spectroscopy (OGRESS)[3], launched in 2015, aimed to observe soft X-rays with a broad field of view whereas OGRE focuses on point source observations. OGRESS was designed to acquire a spectrum of the Cygnus Loop with a resolution of R∼10-40. An unexpectedly high count rate was observed, swamping the spectra acquired. Efforts are being undertaken to extract the useful data from this noise, which seems to be a uniform signal across the detectors active area. OGRESS relied on passive focusers which only allow photons that would form a natural focus on the focal plane to be incident onto the off-plane gratings, sending selected X-rays towards the on-board Gas Electron Multipliers (GEMS) for detection. GEM detectors were chosen as they feature a large collecting area with high quantum efficiency for a low cost but have a low spatial resolution. As OGRE is observing a point source, rather than an extended source, alternative technologies must be used which give a high accuracy in spatial readout and thus a better spatial resolution.

The work discussed in this paper focuses mainly on the detectors that will be used for OGRE and the tests carried out on them so far. In order to understand how and why they are being used in this project, the whole spectrometer design must first be discussed.

The optics will take the form of a Wolter type-1 telescope. This nested optics system will utilise precision cut mirrors made from single-crystal silicon, chosen due to the lack of internal stresses decreasing the systems susceptibility to distortion during manufacture. Each of these mirrors aims to have an angular resolution of <5 arcseconds. Many previous X-ray optic modules were populated using wedges of these mirrors; however, the OGRE payload will have optics comprised of a meta-shell. This alternative optics manufacturing method allows for easier mirror alignment and reduces the costs of production, however, the ability to sub-aperture is lost causing the resolution to be very dependent on the optics resolution[4].

The focused photons are then incident on the off-plane reflection gratings arrays which diffracts the X-rays into an arc that is dependent on the photons wavelength (Figure 2). The spectral resolution is maximised by using a high groove density of 6000 grooves/mm with each groove being blazed. This diffracts the photons to one side of the zero order, removing the need to place detectors either side to capture all the light and therefore optimising the size of the focal plane required. The grooves will also be Variable Line Spaced (VLS) to match the convergence of the incident beam. A new process of grating production is being developed at the University of Iowa to allow the manufacture of large format, high fidelity gratings that can be co-aligned into a grating module. This process combines several fabrication techniques employed elsewhere to develop the specialised gratings for use in the OGRE payload.

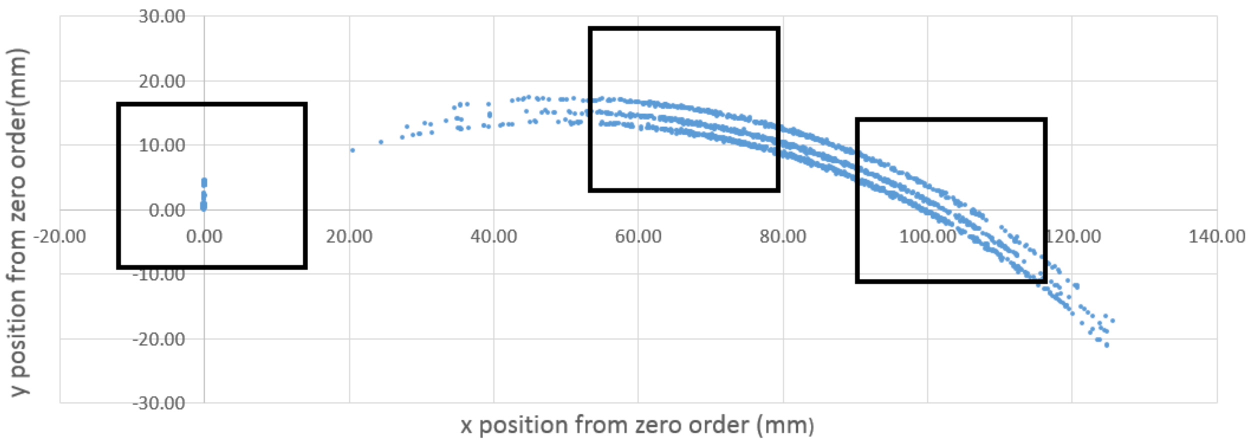

Figure 2. The arcs of diffraction expected to be produced by a previous OGRE optics system. The black boxes represent the image areas of the detectors being used. Not all photons in the arc will fall upon a detector.The gratings will be separated into 3 modules with a 0.5mm offset on each, hence the three arcs.

The focal plane is located ∼3m from the grating module and is where the camera module which houses the camera electronics and the detectors will be installed (Figure 3). The arc of diffraction will be incident on three EM-CCDs, one of which will be located at the zeroth order and will receive a sample of all light that is focused by the optics. The two other detectors will be placed to detect photons from the spectral lines of metal expected to be observed in the Capella spectrum after dispersion from the gratings. A fourth detector will be kept isolated from the photons focused by the optics and will be dark. The images from this device will show noise from the electronics and the rocket. If the data retrieved is similar to that of the OGRESS launch, this fourth detector should drastically improve the efficiency of a decent spectra being extracted from the data.

The launch, scheduled for October 2018 from Wallops Flight Facility, will mark the first instance of an EM CCD being used in astrophysical space-based observations. Charge Coupled Devices (CCDs) have been used extensively in space missions due to their ability to detect a large range of wavelengths.

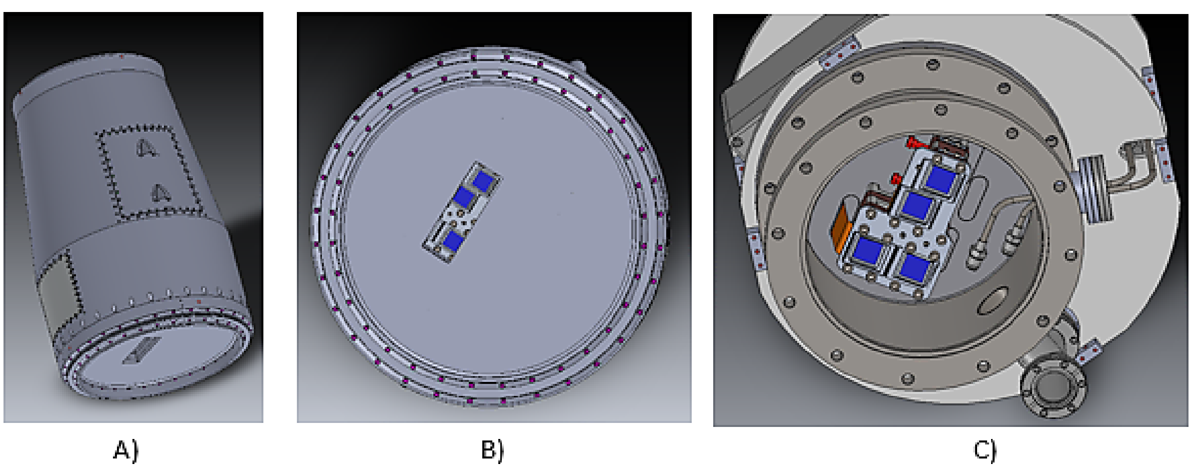

Figure 3. CAD images showing designs for the OGRE camera payload. A) shows the complete camera section of the OGRE payload which will be located 3m from the grating modules. B) shows a face-on view of the camera system with the gate valve allowing three devices to detect photons. C) shows the cold bench on which the four CCDs will be mounted.

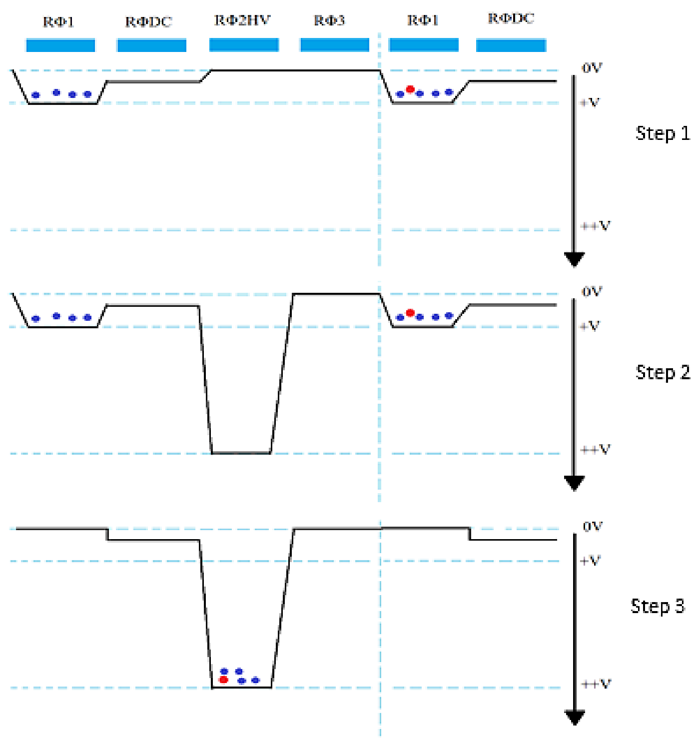

Figure 4. Sequence demonstrating the use of impact ionisation to increase the number of electron is the charge packet. The packet is held in RΦ1 while RΦ2HV is increased (step 2). RΦDC is kept at a low voltage allowing the electrons to flow into the deep RΦ2HV well. As electrons pass into this phase (step 3) there is a small chance they will have enough energy to produce another electron-hole pair, resulting in a larger charge than previously seen (seen by the red dot). This new electron may also produce new pairs in later cells within the multiplication register.

The search for soft X-rays imposes certain requirements on the device needed to detect the photons. The quantum efficiency of a device gives the ratio of incident photons to detected photons. The instrument has a soft energy cut-off (∼0.2keV), that is caused by the low Quantum Efficiencies (QE) experienced by silicon at these energies. OGRE is hoping to make an observation of a very detailed soft X-ray spectra and so it was decided that an alternative detector should be used. The use of an EM-CCD allows low energy events that are detected in the silicon to be more easily reconstructed from the image as their signal is amplified above the detector noise floor. The largest difference between conventional CCDs and EM-CCDs is the multiplication register present in the EM-CCD. Electrons generated in the device by incident photons interacting in the silicon are passed through the multiplication register where there is a chance of the signal being amplified due to impact ionization (Figure 4). This causes smaller signals to be increased by a couple of orders of magnitude before arriving at the readout register. The output amplifier adds a component of noise to the signal which could cover up weaker signals. With EM-CCDs the signal is now much larger before the register. As this readout noise is independent of the signal passed to it, the noise is essentially negligible compared to the large signal and so is suppressed. Faster readouts usually increase the readout noise component added to the signal; however, the ability of an EM-CCD to suppress readout noise reduces this effect allowing images to be taken quickly. Impact ionisation in the multiplication register of an EM-CCD does produce additional shot noise, given by the modified Fano factor[5], which can cause degradation of the spectral resolving power of the detector. It has been found that for our desired photon energies this degradation is small enough to not significantly affect our resolving power[6].

The EM-CCD chosen for use in the OGRE payload, the CCD 207-40 produced by e2v technologies (Figure 5), features an image area comprised of 1600 × 1600 pixels, each of which is 16µm squared. Each detector has a built in multiplication register on one of two readout paths. The readout direction can be changed to allow

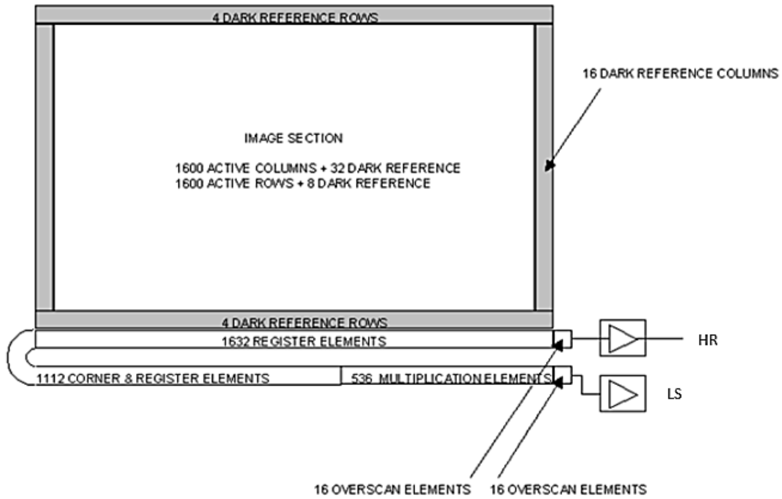

Figure 5. Schematic Chip diagram of the back-illuminated CCD207-40 showing the two readout paths to the large-signal output (LS) and the high-responsivity output (HR)[7].

readout through a standard output or via the multiplication register. The detectors will also be back-illuminated. As the X-rays only have a thin layer of oxide to pass through a greater sensitivity for lower energy photons is achieved than when using the front-illuminated counterpart. Previous synchrotron work with these devices have shown they are capable of observing low energy X-rays like those expected to be seen from Capella[8].

A signal could potentially be split across multiple pixels due to isotropically diffusing electrons within the silicon or due to photons being incident on the silicon close to pixel boundaries. The centroiding of these split events will allow the position at which the photon was incident upon the active silicon to be calculated with sub-pixel accuracy. This improves the spatial resolution of the camera and maximises the resolution of the instrument.

When OGRE is launched, the detectors will be held at -80°C to optimize performance. The rocket will not be carrying any coolant to maintain this temperature and will instead be relying on the thermal mass on which the detectors will be mounted. Before launch liquid nitrogen (LN2) will be used to cool the thermal mass to below -80°C. Heater coils will also be used to raise the temperature of the EM-CCD to the target operating temperature. As the rocket is launched the LN2 supply will be disconnected from the rocket and a built in temperature controller will maintain the -80°C target temperature with the aid of the thermal mass and heaters.

2. THE OGRE TESTING CHAMBER

The camera system has been designed and produced by XCAM Ltd. with a prototype of the final flight build provided to the Open University for testing. This unit features a built in temperature controller, sequencing chips, and four BeagleBone Blacks (BBBs). Each BBB is responsible for storing, and eventually processing, the data from one of the CCD 207-40s that will be used. Cables from the box housing the main system link to a headboard mounted on the outside of the vacuum chamber. This board features four throughput connectors, one for each detector, as well as processors to control the detector sequencing and data control.

For preliminary experiments, an alternative detector is being used. The CCD 207-10 features the same framework as the 207-40 but has an imaging area of 1600 $\times$ 400 pixels. Whilst the final payload will house four back-illuminated devices, the current testing unit is connected to three back-illuminated devices (referred to as detectors 1,2, and 3) and one front-illuminated (referred to as detector 4). The main reason for this discrepancy is the rarity of the CCD207-10 and 207-40. Both detectors are rarely in demand and so supplies of them are low. Flight detectors have been acquired and will be saved for the final integration.

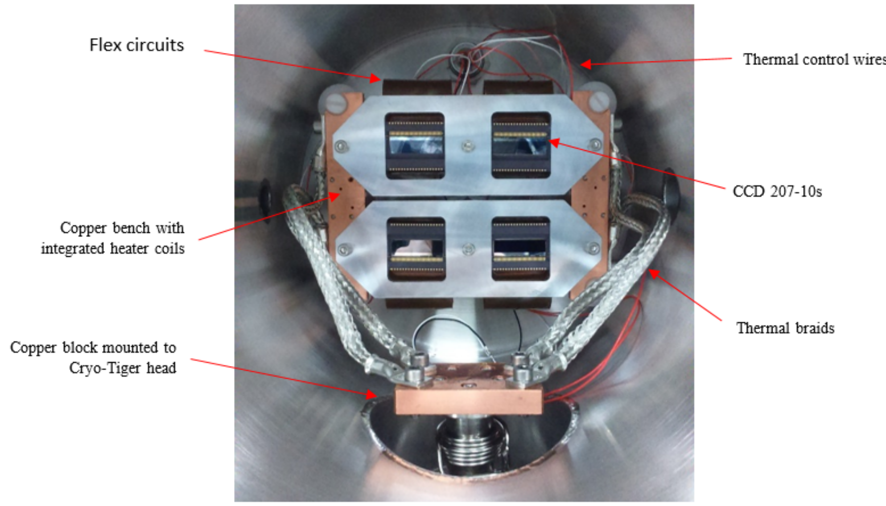

Figure 6. Interior of the OGRE testing chamber. The wiring seen goes to two temperature sensors (PT-1000s) one on each copper unit, and two heater coils housed within the cold bench. Thermal braids can be seen connecting the two thermal units with no contact made to the chamber sides.

Each of the detectors is mounted onto a copper bench inside a vacuum chamber. The copper cold bench houses two heater coils for temperature control and is cooled via braided cables which link to a copper block mounted to a Cryo-Tiger cooling head (seen in Figure 6). Temperature sensors have been installed into both of the copper units to ensure the cooling unit is maintaining temperature control and to allow for experiments in temperature variation. This indirect method of cooling the detectors does mean the full cooling benefits of the Cryo-Tiger cannot be reached however sufficient temperatures can be reached as seen in Figure 7. The chamber is held at $\sim 10^{-5}$ mbar with the cold bench stabilised at -80°C.

The vacuum chamber is capable of hosting a variety of X-ray sources. A sample of iron-55 can be mounted inside the chamber opposite the four detectors. Removing this allows for larger sources to be placed on a connector outside the chamber, i.e. X-ray tubes or Manson sources.

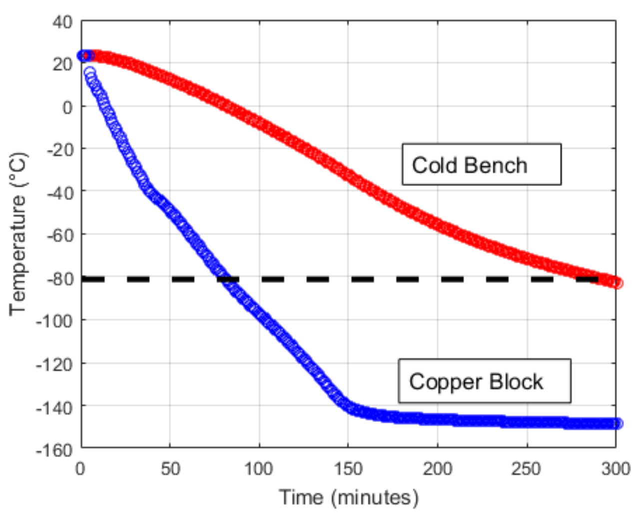

Figure 7. Cooling curve for the OGRE cold bench and the copper block which is attached to the cryotiger head. The heater coils were left off to determine the lowest temperature that can be tested with the current experimental arrangement.

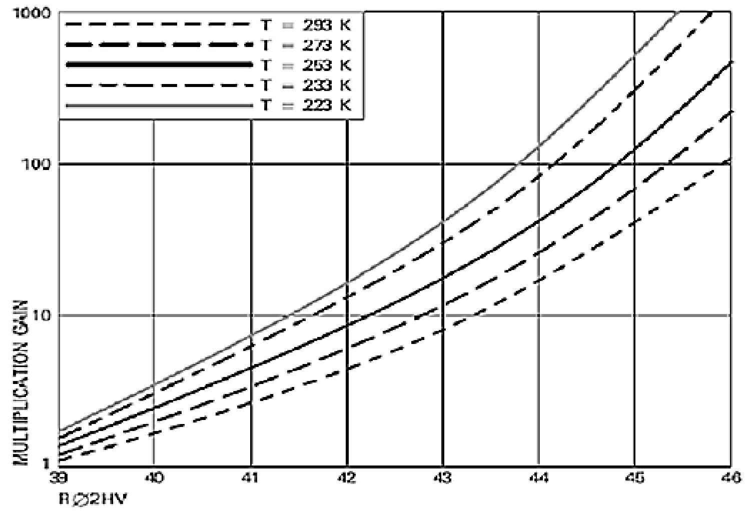

Figure 8. Known HV-gain curves produced at e2v technologies for the Back-illuminated CCD207-40 for a range of temperatures.[7]

3. INITIAL CAMERA CHARACTERISATION

In order to gain a better understanding of the cameras behaviours in certain scenarios it is important to understand the basic principles of its operation. At present, the camera takes a sequential approach to obtaining images from each of the four detectors with the same sequencing and voltages being applied to all the detectors. Whilst all the detectors go through the clocking sequence only one set of data can be saved at any one time slowing down data acquisition. The mix of FI and BI also adds a compilation as they have varying optimal voltages.

The back-illuminated CCD 207-40s have been shown to demonstrate large amounts of gain with increasing RΦ2HV voltages applied as can be seen in Figure 8.

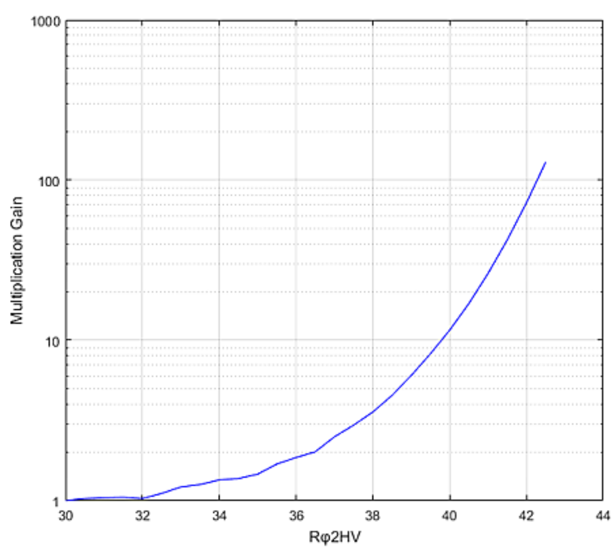

Figure 9. HV-gain curve generated by detector 1 at a temperature of 192.6K. This is typical of the back-illuminated devices that are used for OGREs testing.

The curve seen in Figure 9 was obtained by setting RΦ2HV for voltages ranging from 30V to 46V with a 0.5V testing interval. RΦDC was kept at a constant 3V throughout and the charge packets were passed via the multiplication register each time. At the time of data recording the chamber was held at 192.6K (-80.6°C), a value considerably lower than that seen in Figure 8. Exceeding a voltage of 43V causes a breakdown in the typical HV-gain curve. This appears due to excessive signals forming in the multiplication register which are then exceeding full-well capacity, saturating the analogue to digital converter (ADC) or causing surface channel effects. The multiplication gain has been observed to increase at lower voltages than the data-sheets suggest but follows a similar behaviour until excessive charges are found in the detectors. This behaviour could be typical for these detectors at lower temperatures than those seen in figure 8 but may also be due to the operating voltages and sequencing not being fully optimised for these operating conditions.

4. FUTURE EXPERIMENTS

In order to ensure the optimal performance from the camera when observing Capella, several essential tests must be carried out in advance. A range of photon energies are expected to be incident on the focal plane and so the sensitivity of the detectors to many energies must be tested. Whilst iron 55 guarantees photon energies at 5898 eV alternative sources are required to cover the expected photon energies. The use of X-ray tubes or a Manson source is possible with the facilities available at the Open University to accommodate the majority of these photon energies. If more specific energies are required the use of the PTB beamlines at BESSY II could be warranted to deliver a near continuous stream of monochromatic photons.

The susceptibility of the camera to Electromagnetic Interference (EMI) will also need to be evaluated. The detectors shall be operated in a photon counting mode so any noise from external sources could be a large issue, reporting false detections. Other sources of EMI must also be checked to ensure the signals observed and classified as event photons are indeed photons from Capella rather than EMI. Being able to characterise false signals should allow for them to be identified on-board by the event processing.

The data that can be telemetered from the rocket to the ground is limited and so the ability to process data on-board and send only useful information will be of significant use. It is hoped that the raw data can be saved to a solid state device connected to each of the BBBs as a back-up data recording but being able to see useful information coming back during the flight will let us know the camera is working as desired and that the payload is on target. To save storage space and processing time it has been suggested that each detector be windowed based on the position of the zeroth order. As the arc of diffraction will be of a known shape defined by the optics it should be possible to reduce the area of the detector to the region that will contain photons. This would greatly reduce the readout time for the detectors and thus increase the proportion of 1Hz frame rate that can be used for integrating photons. This smaller data set can then be processed to determine if the signal corresponds to a desired photon or some other event. If the signal is due to a photon the position on the detector on which it was incident can be sent back along with the position of the zeroth order at that time. It is hoped that the event processing utilised by OGRE could be of use in future projects such as SMILE.

The detector performance at various temperatures will also be analysed to see how any warming that may occur during the flight could impact the data received. This will be carried out alongside the variation of X-ray sources and some of the EMI testing. Completing these experiments will help with the analysis of the data if some EMI is present at a temperature that wasnt expected to be reached during operation or if temperature variations are shown to cause a change in the multiplication gain of the camera.

With teams focussing on the many areas of OGRE a second OGRE camera has been built to be used in tests alongside the gratings and optics in the USA while work and improvements on the original prototype are made at the Open University in the UK. To ensure the correct operation of the second camera some of the tests mentioned previously will be done twice to check the resultant data from both cameras closely match. The second system will be sent to the USA in late 2016.

5. SUMMARY

OGRE is scheduled to launch in late 2018. If successful it will provide the highest resolution spectrum of Capella to date and could lead to considerably higher resolutions being seen in future X-ray projects that utilise further advanced forms of the technologies demonstrated in this small-scale mission. The high resolution and low-energy benefits obtained through the use of EM-CCDs could prove advantageous for other future missions and, successful OGRE launch could encourage a more widespread use of these detectors.

6. ACKNOWLEDGEMENTS

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